Stochastic Models and Robust Estimation for Broadband Acoustic Mode Signals

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LONG-TERM GOALS

The long term goals of this project are to investigate stochastic models for broadband mode signals propagating in fluctuating ocean environments and to develop robust signal processing techniques to facilitate estimation of these signals from experimental data.

OBJECTIVES

To develop a greater understanding of broadband mode signals in fluctuating ocean environments, this project focuses on two closely-related research objectives. The first objective is to characterize mode fluctuations at megameter ranges. Mode arrivals at long range are very complicated due to internal-wave-induced coupling. From a theoretical standpoint, the effects of internal waves on long-range sound propagation are not well-understood. Much of the previous work in this area focuses on the ray arrivals because they are amenable to analysis via the geometrical optics approximation. Ultimately we plan to develop a sufficiently general model of mode propagation that explains recent experimental observations and clarifies the relationship between mode and ray representations of the field. The second objective of this project is to design robust mode processors for dynamic ocean environments. Specifically, we plan to develop a framework for mode processing that mitigates the effects environmental mismatch, sensor failures, and interference. Mismatch, in particular, is a problem that plagues many sonar applications, thus this work has implications beyond the current project.

APPROACH

In recent years, several ONR-sponsored experiments have examined long-range acoustic propagation using a network of sources and receivers in the Pacific. The Acoustic Thermometry of Ocean Climate (ATOC) experiment and the associated Alternate Source Test (AST) provided a unique opportunity to observe broadband signals at megameter ranges. Two vertical line arrays (VLA's) installed for these experiments received M-sequences transmitted from two near-axial sources, one mounted on a seamount and the other suspended from a ship in nearby deeper water. The sources were located off the California coast, and the receiving arrays were moored near Hawaii and Kiritimati, at distances of 3515 km and 5171 km, respectively. Several years later the North Pacific Acoustic Laboratory (NPAL) experiment took measurements at similar ranges, using a source off Kauai and a horizontal billboard array off

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14. ABSTRACT

The long term goals of this project are to investigate stochastic models for broadband mode signals propagating in fluctuating ocean environments and to develop robust signal processing techniques to facilitate estimation of these signals from experimental data.

15. SUBJECT TERMS

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California.

This project explores stochastic models and robust signal processing for broadband modes using the rich data set provided by the ATOC and NPAL experiments. The work builds on the short-time Fourier mode processing techniques developed by Wage [1]. By focusing on the modes, the project complements the work of other investigators who are primarily studying the ray arrivals. In addition to the PI, two Ph.D. students are currently working on the project. Aravinda Sringarapuram and Tarun Chandrayadula entered the Ph.D. program at George Mason University within the last year. They are focusing primarily on the signal processing aspects of the project.

WORK COMPLETED

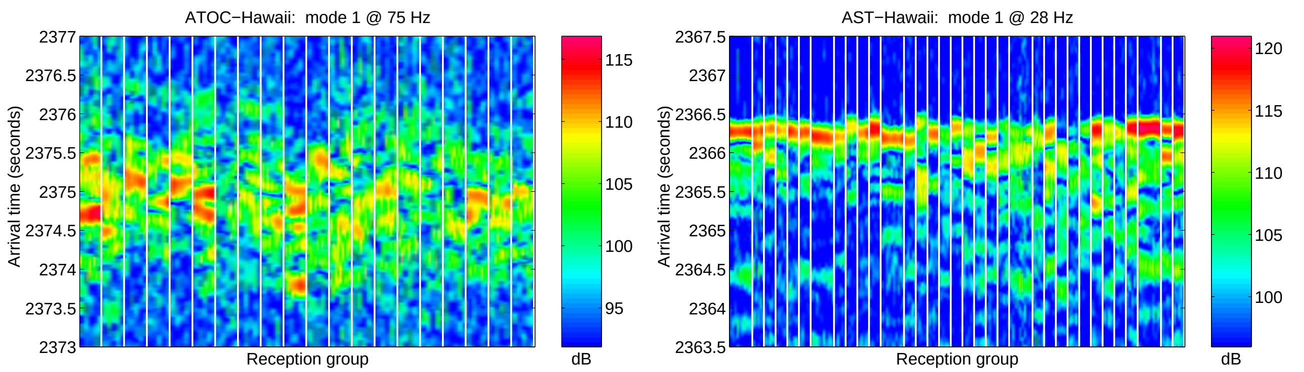
Kathleen Wage analyzed the ATOC Hawaii data set as a part of her Ph.D. thesis [1], written under the supervision of Arthur Baggeroer (MIT) and James Preisig (WHOI). As a part of the current project, Wage substantially revised the mode coherence analysis for the ATOC-Hawaii data set in 2002. These new results, along with others from the thesis, were published in the February 2003 issue of the Journal of the Acoustical Society of America [2].

In the last year, mode analysis has been performed on two additional data sets: 1) the ATOC receptions at the Kiritimati VLA and 2) the AST receptions at Hawaii and Kiritimati VLA's. Kathleen Wage presented results of the Kiritimati mode analysis at the Acoustical Society meeting in May 2003 [3]. A comparative study of the ATOC and AST receptions will be presented at the upcoming IEEE/MTS Oceans conference [4]. As discussed below, the analysis of these data sets reinforces some of the conclusions of the ATOC-Hawaii analysis and suggests further avenues for research. Additional work on the ATOC-Kiritimati and AST receptions is ongoing.

RESULTS

Figure 1 illustrates several important points about low mode arrivals at megameter ranges, gleaned from the comparative analysis of the ATOC and AST data sets. The plots show estimates of mode 1 at Hawaii for the 75 Hz ATOC source and the 28 Hz AST source. The y-axis of each plot represents the arrival time within a single reception. Consecutive receptions are stacked in the x-direction. The VLA's recorded 10 or 20 four-period averages of the M-sequence for each transmission. Vertical white lines in the plots separate the four-period averages within a single transmission from the four-period averages in neighboring transmissions. Transmissions are nominally separated by four hours. Figure 1(a) shows that for the ATOC 75 Hz receptions there is no dominant arrival in mode 1, instead there are a series of arrivals that fade in and out, sometimes disappearing over the period of a single transmission (≈ 20 minutes). There is no strong cutoff in the data; the strongest arrivals are followed by 0.5-1 second of less energetic arrivals. In contrast, the mode 1 estimates for the 28 Hz AST source have one dominant arrival and exhibit a sharp cutoff. Simulations presented in [4] indicate that the sharper cutoff in the AST data is due to the fact that the AST source is located in deep water, rather than on a seamount. The more diffuse finale seen in the ATOC receptions is due to bottom interaction near the Pioneer seamount source.

According to Dozier and Tappert [5], internal-wave-induced scattering decorrelates the mode signals. In [2] we examined the coherence of the first 10 modes in the ATOC Hawaii receptions using magnitude-



(a) ATOC 75 Hz source

(b) AST 28 Hz source

Figure 1: Estimated mode 1 time series at Hawaii for the ATOC and AST sources. Arrival time is shown along the y-axis. Consecutive receptions are stacked along the x-axis. During each transmission the VLA recorded 10 or 20 four-period averages. Vertical lines separate the transmissions, which occurred at intervals of at least four hours.

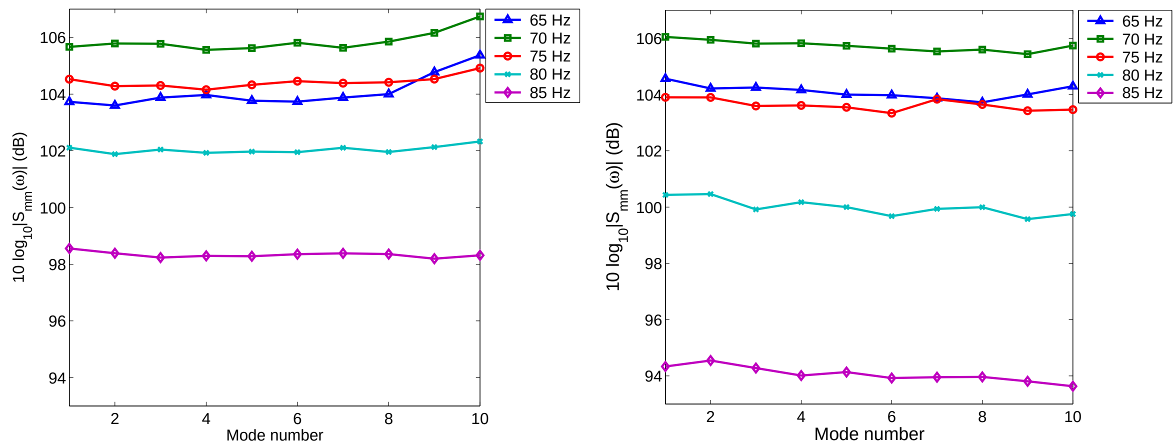
squared coherence (MSC) as a metric. The MSC of two random processes is defined as [6]

$$\mathrm{MSC}(\omega) = \frac{|S_{xy}(\omega)|^2}{S_{xx}(\omega)S_{yy}(\omega)}, \tag{1}$$

where S_{xy} is the cross power spectral density and S_{xx} and S_{yy} are the auto power spectral densities. Figure 2 shows the average power estimates ($10\log_{10}|\widehat{S}_{mm}|$) as a function of mode number for the first 10 modes in the 65, 70, 75, 80, and 85 Hz bins. The left plot shows the results for the ATOC Hawaii receptions discussed in [2] and the right plot shows similar results for the ATOC Kiritimati receptions. For these low modes, the experimental data show that the average power is approximately constant in each bin. This is consistent with Dozier and Tappert's prediction of an equipartitioning of energy among the modes. The differences in absolute levels from bin to bin are a function of the source spectrum.

Analysis of the Hawaii and Kiritimati data sets show that the maximum cross-mode coherence for any of the first 10 modes (computed from Equation 1) is less than 0.1 [3]. This supports another of Dozier and Tappert's claims, that the modes decorrelate with range due to internal-wave scattering. Note that in comparing to Dozier and Tappert's predictions, it is important to stress that the experimental measurements have only been done for modes 1-10 (the modes spatially-resolved by the array). Higher order modes, which constructively interfere to form the ray arrivals, may behave differently.

Figure 1 demonstrates that arrivals in mode 1 fluctuate substantially over time, with individual arrivals fading in and out over the duration of a single 20-minute transmission. We use the MSC metric to quantify the temporal coherence of these arrivals. Figure 3 shows the MSC for the ATOC and AST mode 1 arrivals at the Hawaii and Kiritimati arrays. At 75 Hz, mode 1 decorrelates rather rapidly reaching MSC=0.5 at 4.5 minutes. Interestingly, the results for the two arrays are in good agreement, suggesting that temporal coherence does not change much with range beyond 3500 km. The experimental results also show excellent agreement with a narrowband simulation of propagation through internal waves. At 28 Hz, both the experimental data and the simulation results show a marked increase in temporal



(a) ATOC: Hawaii average power estimates

(b) ATOC: Kiritimati average power estimates

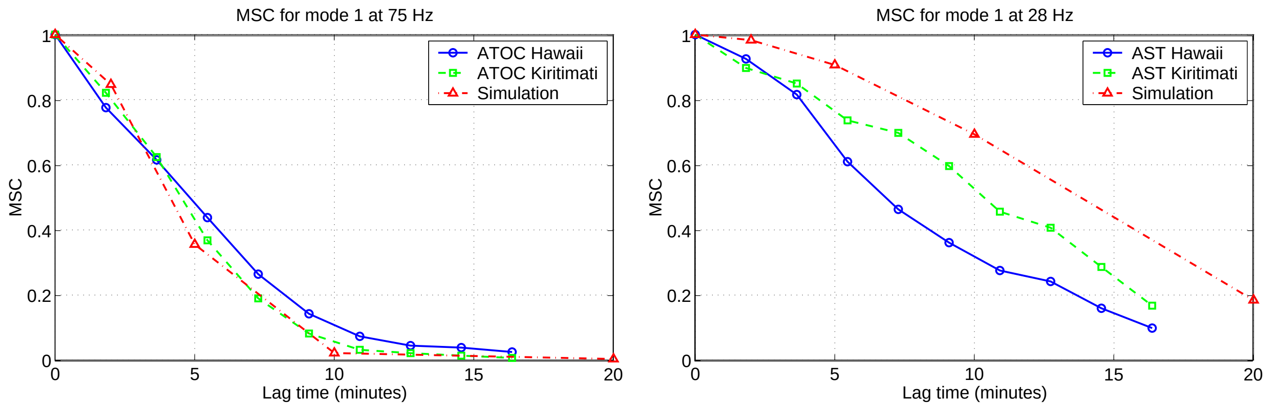
Figure 2: Average power as a function of mode number in the 65-, 70-, 75-, 80-, and 85-Hz bins estimated from the ATOC receptions at Hawaii and Kiritimati.

coherence. This is expected since internal wave scattering is known to be less severe at lower frequencies. The agreement between the experimental estimates and the simulation is not as good at 28 Hz as it is at 75 Hz. Further work on the temporal coherence estimates is underway, with one of the goals being to compute confidence limits for the coherence estimates.

In addition to temporal coherence, we plan to measure the horizontal coherence of the mode signals. The billboard array deployed as a part of the NPAL experiment facilitates such measurements. Before the NPAL data set can be used to analyze the horizontal coherence of the low-order modes, several signal processing obstacles must be overcome. The first obstacle is the incomplete knowledge of the sound speed at the NPAL array. Sensors on the array measured the temperature at the hydrophone depths, but the temperature above the array is unknown. Thus we can calculate the sound speed over the span of the array, but not for the entire water column. In general the complete sound speed profile is needed to compute the mode shapes and wavenumbers required for designing the mode filter. The second obstacle in processing the NPAL data is the failure of several of the hydrophones on the long array. Three of the failed hydrophones are adjacent to one another, causing crosstalk problems for the conventional least squares mode filter. The final obstacle is the interference from signals propagating in higher-order modes. This interference is more severe in the NPAL data than in the previous experiments due to upslope coupling near the billboard array. At present we are investigating new methods of designing mode filters that are robust to imperfect environmental knowledge, sensor failures, and interference. Although the NPAL analysis is the motivation for the research on robust mode filters, we anticipate that the results will be applicable to other experimental scenarios.

IMPACT/APPLICATIONS

The objectives of this research have both scientific and operational applications. The low-order modes are associated with the most energetic arrivals at long range and are potentially useful in tomography and matched field processing (MFP). From a scientific standpoint, authors such as Munk and Wunsch [7]



(a) ATOC: MSC at 75 Hz for mode 1.

(b) AST: MSC at 28 Hz for mode 1

Figure 3: Temporal coherence estimates for the ATOC and AST receptions. The plots show magnitude-squared coherence for mode 1 as a function of the lag time between the first four-period average and successive four-period averages. The ATOC and AST curves were derived from groups of 20 and 34 receptions, respectively. The simulation result was derived from 30 narrowband parabolic equation runs for a realistic environment containing internal waves.

have proposed using modes in large-scale ocean monitoring, such as thermometry. From an operational standpoint, matched field source localization has great potential to improve fleet sonar capabilities if the problems with environmental mismatch can be overcome.

Using broadband mode signals as observables in either tomography or MFP requires a thorough understanding of how modes propagate in inhomogeneous environments and reliable techniques for estimating them from imperfect measurements of the pressure field, both of which are addressed in this work. Specifically, the mode fluctuation statistics calculated in this work may be useful in other modeling efforts. Also, the robust mode processing schemes explored in this project should be applicable in both short- and long-range propagation scenarios.

RELATED PROJECTS

This work is closely related to the ONR-sponsored North Pacific Acoustic Laboratory (NPAL) project since it relies on experimental data collected by the NPAL group (see http://atoc.ucsd.edu/npal/). Kathleen Wage regularly attends the NPAL Data Analysis Workshops and plans to participate in the upcoming NPAL-04 experiment. At the August 2002 and March 2003 workshops, she presented talks on recent mode processing results for the ATOC and AST data sets and on array design for NPAL-04. In June 2003, she prepared a short memo on array design issues related to mode processing at the request of NPAL PI Peter Worcester.

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